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BLOCKCHAIN-BASED IDENTITY MANAGEMENT SYSTEM: COMPREHENSIVE IMPLEMENTATION WITH BIOMETRIC AUTHENTICATION AND VERIFICATION

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Abstract

Digital Identity Management is central to online interactions in financial, healthcare, and governmental domains. However, the traditional systems are centralized, suffering from single points of failure, identity theft, and lack of user control. This paper proposes a blockchain-based decentralized identity management framework that utilizes Distributed Ledger Technology for secure, tamper-resistant, and user-controlled verification of digital identity. The proposed system uses Self-Sovereign Identity and Decentralized Identifiers for user-centric identity governance, removing dependence on central authorities. This paper introduces a new implementation of a decentralized identity management system tailored for national identity credentials by using Ethereum smart contracts in combination with integrated facial biometric authentication and behavioral liveness detection.

Our system architecture introduces a three-entity model of Issuer, Holder, and Verifier that enables trusted credential issuance with decentralized verification while storing all PII off-chain. Newness lies in:

Hash-anchored government-level identities with cryptographic commitments in practice.

Integrated facial biometric authentication with liveness detection to prevent spoofing attacks.

Local wallet storage encrypted via PBKDF2-SHA256 key derivation; 200,000 iterations provide 256-bit equivalent security strength.

End-to-end workflow functionality preserving privacy through layered encryption.

The system is deployed and tested on Ethereum Sepolia testnet with formal security analysis of the cryptographic properties. Experimental results validate sub-second credential verification, < 2% false rejection rate for face authentications, and complete protection against presentation attacks using behavioral liveness checks. This architecture enforces role-based access control through smart contract modifiers and demonstrates practical feasibility for government-scale deployment.

INTRODUCTION

1.1 Background and Motivation

In a digitizing world, people and organizations alike rely on digital identities to validate access to online services. Traditional identity management models are centralized, through the information provided by third-party authorities such as governments, financial institutions, or big technology companies. This centralization invites several weaknesses: one compromised database can result in numerous data breaches, identity theft, and violations of privacy. A 2024 IBM Security report estimated an average cost of over USD 4.88 million for a data breach, with records of identities being among the most attacked targets.[1]

1. ***Single Point of Failure:*** If central infrastructure is compromised, all citizens' data is exposed.
2. ***Credential Forgery:*** Digital and paper credentials are not tamper-evident.
3. ***Data Breach Susceptibility:*** Centralized storage concentrates privacy risks.
4. ***Limited Interoperability:*** Credentials issued by one authority are difficult to verify internationally.
5. ***Verification Friction:*** Verifiers need to connect with the issuing authorities to verify the legitimacy of claimed credentials, which in turn creates latency and increases costs.
6. ***Opacity and Auditability:*** Private record-keeping restricts transparency and third-party verification.[2]

Decentralization, immutability, and cryptography are representing an alternative paradigm created by blockchain technology. Blockchain allows the decentralized storage and verification of the identity credentials, as opposed to a centralized identity provider. Every transaction gets consensus among a network of nodes, which ensures that no single entity could unilaterally influence or change user data. This characteristic makes blockchain-based systems ideal for developing self-sovereign identity frameworks where individuals own and manage their credentials without intermediaries.

- **Immutability:** Through cryptographic commitment, past credential values cannot be changed retroactively.
- **Transparency:** All transactions and state changes are publicly auditable.
- **Decentralization:** No single point of control or failure.
- **Programmability:** Smart contracts enforce credential lifecycle rules and authorization.
- **Non-repudiation:** Cryptographic signatures ensure authenticity and accountability.[3][4][5][6]

In spite of the rapid digital transformation, traditional identity management systems remain highly susceptible to data breaches, identity theft, single points of failure, and a lack of user control over personal data. These systems are based on a model of trusted third-party stored identities that have raised several issues concerning privacy, security, interoperability, scalability, and regulatory compliance.

As such, blockchain technology has emerged as a possible solution because of its immutability, decentralization, cryptographic trust model, and auditability. The integration of blockchain with identity management introduces unresolved challenges, including:

- Manage Personally Identifiable Information effectively without exposing sensitive data on-chain.

- Scalability, low latency, and high throughput for identity verification.
- Designing interoperable standards across institutions, applications, and jurisdictions.
- Balancing privacy-preserving mechanisms involving zero-knowledge proof with transparency.
- Designing user-friendly identity recovery mechanisms without compromising security.
- Understanding and applying legal frameworks, such as the requirements of GDPR, which prohibits the permanent storage of private data.
- Assessing cost, energy consumption, and feasibility in real-world deployments.[7]

1.2 Research Gap and Contribution

Current blockchain identity systems have three main limitations when applied to national identity contexts:

- **Limitation 1 – Trust Model Incompatibility:** Most systems assume distributed trust, while government identities require centralized issuance with decentralized verification.
- **Limitation 2 – Privacy-Utility Trade-off:** Existing solutions compromise either privacy through exposing data on-chain or utility by introducing complex cryptographic protocols that require specialized expertise in order to be used effectively.
- **Limitation 3 – Implementation Complexity:** Most academic proposals remain theoretical without any practical validation or guidelines about how to deploy the system in practice.

The main contributions of our paper address the following gaps:

1. ***Complete Working Implementation:*** Hash-anchored national identity credentials deployed on Ethereum Sepolia testnet; end-to-end functionality demonstrated.

Hybrid Trust Model: Keeps government authority for issuance while enabling decentralized peer-to-peer verification without dependency on issuer infrastructure.

Integrated Biometric Security: Facial recognition with behavioral liveness detection—blink detection, head movement analysis—prevents presentation attacks.

Cryptographic Security Analysis: Formal analysis of the security of PBKDF2 key derivation (200,000 iterations, 256-bit strength), Fernet encryption (AES-128-CBC with HMAC-SHA256), and smart contract access control.

Practical Privacy Preservation: PII on-chain integrity proofs using SHA-256 hashing enable verification while keeping sensitive data off-chain.

Performance Characterization: Quantified metrics include face encoding extraction (200–500ms), credential verification (<500ms), false rejection rate (<2%), and transaction confirmation (3–5 minutes on Sepolia).

Deployment Guidance: Concrete recommendations for government and institutional adoption.

2. Literature Review

2.1 Evolution of Identity Management

Digital identity systems have evolved from centralized architecture, in which a single organization manages user credentials, to federated and decentralized models. Centralized systems, such as OAuth, SAML, and OpenID Connect, depend on trusted authorities but suffer from data breaches and single points of failure. On the other hand, decentralized systems based on blockchain achieve distributed trust

among nodes of the network, hence improving privacy and resilience.[8][9][10]

A recent review by V. Gujar (2024) underlines that blockchain-enabled identity solutions will have a major effect on reducing identity fraud through storing immutable data and verifiable credentials using distributed consensus. These form the basis for stateless-based SSI frameworks.[11]

2.2 Blockchain-Based Identity Management Systems

Identity management using blockchain relies on distributed ledgers to log and verify user identifiers and credentials. K. Samunnisa and S.V.K. Gaddam present that blockchain removes intermediary trust dependencies by associating every identity with cryptographic keys and DIDs. This structure has improved the integrity of authentication and ultimately gives traceability to each transaction of credentials.[12]

In line with this, A. Ganjeer and S. Choubey reviewed the evolution of blockchain-based identity management from conceptual models of SSI to implementation in sectors such as finance, healthcare, and public services, into 2025. Their analysis shows that blockchain enhances not only verification efficiency but also interoperability across domains using open DID standards.[13]

2.3 Self-Sovereign Identity (SSI) and Decentralized Identifiers (DIDs)

The SSI model eliminates the need for intermediaries, enabling individuals to possess their digital identities. Decentralized Identifiers (DIDs) are distinctive identifiers that users generate and manage independently on blockchain networks. In the SSI model, Issuers, Holders, and Verifiers interact through verifiable credentials that are anchored on-chain to ensure authenticity while safeguarding sensitive information.

In their 2025 study, S.N. Lohar et al. proposed a context-aware self-sovereign identity framework for decentralized credential verification. Their system employs blockchain technology to manage the lifecycle of credentials and generate decentralized identifiers (DIDs), thereby reducing reliance on centralized registries. Similarly, R. Raj and S. Gupta examined blockchain-based decentralized identification systems that integrate the principles of sovereign identity to guarantee robust privacy and user autonomy in 2025.[14][15]

2.4 Comparative Frameworks and Implementations

Hosseini et al. give a thorough look at blockchain-based decentralized identification frameworks for IoT. They stress how the SSI principle makes it possible for machines to authenticate each other without trusting anyone. It then points out that scalability and privacy leakage are major problems that make it hard to use in the real world.[16] In a separate empirical study, L. Rota created and combined a self-sovereign identification platform that used DIDs and credentials that could be verified. The framework was tested using Hyperledger Indy, which proved that it could issue and verify credentials quickly and with the least amount of delay. In the same way, F.M. Tiham et al. suggested a trust registry concept to make issuer verification more reliable in decentralized identity ecosystems.[17][18]

3. Background and Related Work

*3.1 Centralization vs. Decentralization vs. **Distributed** Paradigms*

Centralized Systems: Operate under single organizational control, offering ease of management but introducing

single points of failure and attack vectors. Traditional government databases epitomize this paradigm, in which authority and vulnerability alike are concentrated.

2) **Decentralized Systems:** Authority is distributed across autonomous nodes—such as blockchain networks—to reduce the probability of a single point of failure, though this approach requires complex coordination mechanisms and consensus protocols.

3) **Distributed Systems:** These systems split up tasks and data across independent nodes, generally using distributed databases. They provide for high scalability but at the cost of consistency maintenance and various other coordination-related challenges.[19][20][21][22][23]

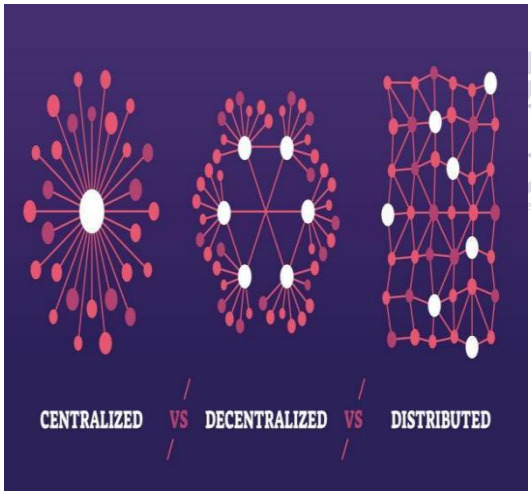


Figure 1: Difference Between Centralized,Decentralized,Decentralized Systems.

Our implementation uses hybrid architecture: the issuer retains hierarchical control over credential issuance, while verification is performed in a fully decentralized manner using the public blockchain infrastructure of Ethereum. This balances the need for government authority with the requirement for empowering citizens within the self-sovereign identity framework.

3.2 Cryptographic Foundations

Cryptography provides a mathematical basis for digital security, including confidentiality, integrity, authentication, and non-repudiation.
I. **Symmetric Cryptography:** Single shared keys (AES, DES) provide for efficient encryption; however, the key exchange must be done in a secure way.
II. **Asymmetric Cryptography:** Public-private key pairs (RSA, ECC) enable secure key distribution and digital signatures without pre-shared secrets.
III. Hash Functions: Produce fixed-size deterministic fingerprints, enabling integrity verification without exposing original content.[24][25][26]

Our system relies on three cryptographic primitives:

Cryptographic Hashing (SHA-256): Produces deterministic 256-bit digests of credential data, allowing integrity to be checked without exposure of PII. Mathematical property: $\text{hash}(M) = \text{hash}(M') \iff M = M'$ (collision resistance provides security).

Key Derivation (PBKDF2): A method for obtaining encryption keys from passwords by iteratively hashing. Using 200,000 iterations and SHA-256: derived_key = PBKDF2(password, salt, 200000, SHA256, 32 bytes). Computational cost per attempt ≈ 80ms—making brute-force attacks computationally infeasible.

Authenticated Encryption (Fernet): AES-128-CBC (confidentiality) and HMAC-SHA256 (authenticity) are combined to prevent tampering, with constant-time comparison mitigating timing attacks.

3.3 Identity Management using Blockchain Technology

Blockchain technology empowers decentralized transaction documentation

and authentication through distributed ledgers possessing critical properties:

1. **Decentralization:** No single point of failure; resilient to censorship and manipulation.
2. **Immutability:** Identity information, once documented, cannot be changed without network consensus.
3. **Public Key Infrastructure (PKI):** Provides cryptographic security for authentication and verification, offering tamper-resistant operations.
4. **Smart Contracts:** Programmable enforcement of rule-based verification, minimizing human intervention, and simplifying compliance.[27][28][29][30]

3.4 Related Identity Systems

A lot has changed in decentralized and blockchain-based identity systems. A few big projects have changed the way digital identity systems are made today. The Sovrin Foundation and Hyperledger Indy use the W3C Verifiable Credentials Data Model and Decentralized Identifiers (DIDs) to make transactions of identity safe and hard to change. Their frameworks also include zero-knowledge proofs, which let you share user information without giving up raw data, but only when you want to. But these systems need their own network of validator nodes and infrastructure, which makes them more expensive to set up and harder to run. Also, they don't have built-in ways to use biometric authentication or liveness detection, which makes them less safe for high-security identification uses like government, finance, or border control.[31][32]

The Microsoft ION Project has a different architecture because it is a Layer-2 DID network that is linked to the Bitcoin mainnet. ION is based on the Sidetree protocol and lets you do big DID operations without a standard blockchain smart contract layer. This method is more open and works better with other systems around the world, but it also depends on how fast Bitcoin transactions can be processed and confirmed. The system is hard to set up, and it might have trouble verifying identities in real time or with a lot of people because it can't grow and relies on outside anchoring mechanisms.[33]

The Ethereum ecosystem is utilized by other well-known systems like uPort and Civic to offer user-controlled, autonomous identification solutions. By granting people direct control over their cryptographic keys and identity claims, these services put user autonomy first. These systems perform poorly when compared to government-grade identity requirements, even though they are appropriate for general-purpose identity and authentication scenarios. They have weak liveness detection capabilities, provide little biometric integration, and frequently rely on centralized components for account restoration and key recovery, which could lead to single points of failure.Additionally, the high cost and variability of Ethereum network fees may hinder their adoption for large-scale public sector identity applications.[34][35][36]

Our System Differentiation with other System:

Blockchain	Ethereum Public	Bitcoin (L2)	Hyperledger Indy	Ethereum
Identity Type	Government-issued	Self/organizational	Org/self-issued	Self/org
On-chain PII	None (hash only)	None	None	None
Biometric Integration	Facial + liveness	No	No	Limited
Revocation Support	Yes (deletion)	Sidetree-dependent	Yes	Yes
Selective Disclosure	No (ZKP planned)	Pluggable (WIP)	Yes	Yes
Implementation	Working	Production	Production	Production
Deployment Barrier	Low	High	Very High	Medium
Security Analysis	Formal	Industry	Theoretical	Industry

4. System Architecture

The suggested system is founded on the standard model of the Verifiable Credential, which involves three primary participants:

1. Issuer: An organization authorized to issue credentials.It may be Government or any Issuance Department. In our implementation, this is an authority (e.g., National Database and Registration Authority) that certifies the identity of a user. The Issuer has the right to write only a smart contract. A smart contract is already written by the Issuer. In which they ask User Information and send them to their Wallet address through Blockchain.

2. Holder (User): This is the owner of the credential. The address of the Holder on Ethereum wallet serves as their Decentralized Identifier (DID). The Holder is the off-chain storage of actual credential data and no-one can see the Holder personal Information.

3. Verifier:This organization must verify that the credential of a holder is valid. This may be a bank, airport, or any service that involves identity checking.It just put the User Wallet address in the System and system will show that the User is Verified or not.[37][38][39]

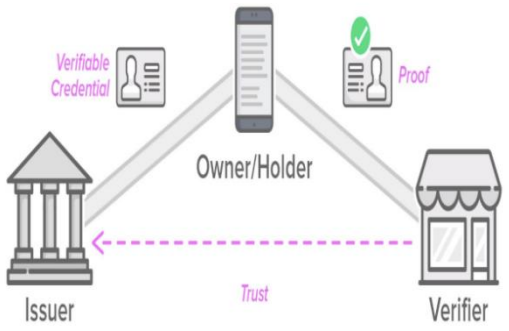


Figure 2:The Triangle of Trust model for Verifiable Credentials, illustrating the relationship between the Issuer, Holder (User), and Verifier.

This architecture differs from existing models by:

- Maintaining hierarchical trust for issuance.
- Enabling peer-to-peer verification.
- Separating data storage from verification logic.

Issuer	Provides credentials to users (e.g., government, university)	"IssueCredential()"
Holder/User	Owns and controls their identity credentials	"RequestVerification()"
Verifier	Validates credentials for authenticity	"VerifyCredential()"

4.1 ***Layer of the System***

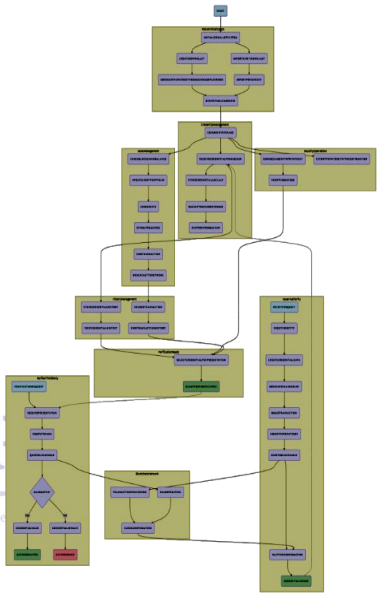
The proposed solution employs a multilayered architectural framework to delineate issues, enhance modularity, and maintain a high degree of cryptographic assurance. The digital credential lifecycle has four steps: issuing, storing, checking, and making sure it can't be changed. They all work together to create a safe and efficient decentralized identity system.

1. ***The Blockchain Level:***The system is built around an Ethereum-based smart contract. It serves as a secure record of credentials. This layer only keeps hashes of credentials, not personal information. It also gives you the logic you need to check who owns credentials and how real they are. Once a credential hash is recorded on the blockchain, it can't be changed or erased without being noticed because the blockchain is immutable and decentralized. The user's identifying information and metadata make up each credential hash. This makes sure that it is unique and can't be faked. The layer also keeps a clear record of all credential issuance events, which makes it safe to use in places where trust is very important, like government, healthcare, and education.

The issuance layer is run by an approved institution, such as a government agency, university, or certifying authority. This organization is in charge of creating and approving user credentials. When an authority gives someone a credential, it makes a cryptographic hash of the user's verified data and sends it to the blockchain smart contract along with the user's wallet address. This method makes an unchangeable record on the blockchain that links the credential to its real owner. The issuance layer is also in charge of signing transactions, keeping track of fees, and built-in checks (like stopping duplicate issuance). The

solution lowers the risk of centralization and supports self-sovereign identification principles because the authority does not keep or control user keys.

3. ***Storage / Wallet Layer:*** The user wallet is where the user's private keys, off-chain credential data, and proofs stored on their computer are kept safe. Users have complete control over their private data because the blockchain only stores hashes. They can keep their information safe by encrypting it and putting it on their device or in a secure local storage module. This layer gives citizens power by giving them sole control over their identity credentials, stopping illegal access, and getting rid of the need for centralized databases. Wallets may also have backup options, QR codes for showing credentials, and the ability to work with W3C Verifiable Credential formats. This helps users show proof to verifiers without putting private information at risk.
4. ***Verifying Layer:*** The hash of the credential that the user gives is compared to the hash that is stored on the blockchain to make sure it is correct. A verifier gets the user's credential (or proof based on it) and figures out the hash on their own. The verifier uses the user's wallet address as a key to get to the hash that is stored in the smart contract. If the hash that was calculated matches the record on the blockchain, the credential is real, hasn't been changed, and was given out by the right person. There is no need for a middleman in this process, so it happens right away and is safe. Advanced verification workflows might include checking timestamps, asking about the status of credential revocation, or selectively disclosing information based on zero-knowledge evidence.
5. ***Smart Contract Structure:***The Ethereum smart contract is the main record for the whole identification system. The basic structure is a mapping that links each user's blockchain address to a 32-byte cryptographic hash that shows the credential that was given. Additional features might include updating or revoking credentials, delegating permissions, and logging events for transparency. The fact that the contract can't be changed after it's been deployed guarantees its long-term integrity and gives everyone a reliable point of trust.



5. Methodology

5.1 Issuer Module

The Issuer Module is a piece of Python software that makes, hashes, and stores user credentials on the blockchain. Its main job is to turn verified user information into a secure, tamper-proof digital credential without putting any personally identifiable information (PII) on-chain.

Making Credentials: The process begins with the Issuer checking the user's public wallet address and personal information,

such as their full name, father's name, home address, city, and date of birth. We put this information into a structured JSON format so that hashing is always the same and can be done on any system. The JSON structure makes sure that the fields are in the right order so that the hash results are always the same.

2. ***Cryptographic Hashing:*** The module serializes the credential JSON object using UTF-8 encoding and then encrypts it using SHA-256 hashing. This step makes a 32-byte cryptographic fingerprint that shows exactly what the credential says. The hash keeps all personal information private and stores the identity off-chain. The answer is to store the hash on the blockchain, which keeps private information safe. This also protects against the worries that come with the GDPR about storing PII in public. The SHA-256 hash also keeps collisions from happening, which means that even small changes will make the hashes look very different.
3. ***Blockchain Transaction:*** The Issuer uses the Web3.py framework to create and sign a transaction to the deployed smart contract's issueCredential() function. You use the Issuer's private key, which is kept safe in environment variables or an encrypted .env store, to show that someone is in charge. The transaction includes both the user's wallet address and the hash of the credential that was calculated. After the hash is sent, the Ethereum network checks it and saves it permanently in the smart contract's state. This unchangeable anchoring makes sure that any future credentials given off-chain can be checked against the hash stored on-chain in a secure way. You can also keep the date, block number, and transaction receipt to keep track of your compliance or audit trails. The issuer module also keeps a local record of each issuing event so that it can be checked, errors can be fixed, and things can be kept track of. You can also add optional tools for limiting rates and checking identities to stop abuse or repeated attempts to issue.

5.2 Holder Module

The Holder Module is a digital wallet and identity manager that keeps users safe. It was built in Python with strict security measures to protect private keys, local credentials, and biometric templates. This module is based on the idea of self-sovereign identification (SSI), which means that users are in charge of their own credentials.

Managing your identity and wallet: All you need to do to set up a wallet is choose a username and password. The module uses PBKDF2 key derivation with at least 100,000 iterations to make encryption keys that keep the user's private key file safe. Brute-force attacks are much less likely to work because of all these iterations. The wallet system lets people in by using both passwords and facial recognition. The liveness-detection and face-matching pipeline in the wallet makes sure that only the real owner can unlock their credentials. The wallet won't do any cryptographic tasks, like signing transactions, unless it can prove that it is alive.

Storing Credentials: The Holder gets the original JSON credential from the Issuer in a safe way, either through an encrypted transfer or a QR code-based handoff. The credential is stored on the device itself and is encrypted with keys from PBKDF2 and a salt that is different for each user. This keeps credentials from ever being sent out in plain text. The module also keeps a record of when

credentials were added, changed, or checked in a local file.

3) ***Wallet Functionality:*** The Holder Module is not only an identity management tool; it is also a simple cryptocurrency wallet. Users can see their assets, send money, sign messages, and look at the history of their transactions. Signing activities never show private keys in their raw form; instead, they happen inside the encrypted wallet. You can easily add extra features like signing with a QR code, making transactions while you're not connected to the internet, and supporting multiple accounts. The holder can also make encrypted backup files that can be used to get back on track after a disaster.

5.3 The Verifier Module

The Verifier Module is a short Python program that lets other people, like schools, service providers, or government agencies, check to see if a user's digital credential is real. It is easy for everyone to validate because the verifier doesn't need access to private blockchain keys or special software.

1. ***Presentation (Sending Credentials Off-Chain):*** The Holder gives the verifier their public wallet address and the JSON credential that was sent to them. The solution protects privacy by letting the Holder and the Verifier talk to each other about PII directly off-chain. This lets the verifier see what's inside.
2. ***Search on the chain:*** Web3.py is used by the Verifier to get to the smart contract's read-only credentials() function. This gets the on-chain credential hash that goes with the holder's wallet address. This call doesn't use any gas, so it's very quick to verify and easy to scale.

Local Hashing: The Verifier uses the same SHA-256 hashing method as the Issuer to check that it is real. The hash that was calculated on the holder's computer is exactly what they said it was. If the credential was changed in any way, such as being updated, forged, or corrupted, the hash would be different from the on-chain value.

Checking: Lastly, the Verifier compares the local hash to the hash on the chain. A match means that
The credential belongs to the wallet address that was given.
An authorized issuer gave it out.
It hasn't been changed or messed with.

If the two hashes match, the credential is real. If not, the verifier won't accept the credential right away. This cryptographic verification means that centralized databases or people looking at documents are no longer needed. It also lets people trust each other without having to wait for results.

6. Technical Implementation

6.1 Smart Contract Implementation (Solidity)

```
pragma solidity ^0.8.20;

contract VerifiableCredentialRegistry {
    // Immutable issuer prevents unauthorized credentials
    address public immutable issuer;

    // Mapping from citizen address to credential hash
    mapping(address => bytes32) public credentials;

    // Events for transparency and auditability
    event CredentialIssued(address indexed citizen, bytes32 indexed hash, uint256 timestamp);
    event CredentialRevoked(address indexed citizen, uint256 timestamp);
```

```
    modifier onlyIssuer() {
        require(msg.sender == issuer, "Unauthorized issuer");
        _;
    }

    constructor() {
        issuer = msg.sender;
    }
}
function issueCredential(address _citizen, bytes32 _hash) external onlyIssuer {
    require(_citizen != address(0), "Invalid citizen address");
    require(_hash != bytes32(0), "Invalid credential hash");
    credentials[_citizen] = _hash;
    emit CredentialIssued(_citizen, _hash, block.timestamp);
}
function revokeCredential(address _citizen) external onlyIssuer {
    require(_citizen != address(0), "Invalid citizen address");
    require(credentials[_citizen] != bytes32(0), "No credential to revoke");
    delete credentials[_citizen];
    emit CredentialRevoked(_citizen, block.timestamp);
}
function verifyCredential(address _citizen, bytes32 _hash)
    public view returns (bool)
{
    return credentials[_citizen] == _hash &&
        credentials[_citizen] != bytes32(0);
}
```

Smart Contract Overview

The smart contract for the VerifiableCredentialRegistry uses an issuer authority that can't be changed to make a simple and secure system for checking credentials on the blockchain. The deployer is permanently named as the issuer when the contract is deployed. This means that only this person can create, change, or revoke user credentials. The system only keeps hashes of credentials, not any personal information. This keeps users' information private while still letting integrity checks happen. There is a unique bytes32 cryptographic hash that links a citizen's address to their credential. When the contract is issued and revoked, it sends out events. This lets you audit and keep an eye on things outside of the chain. When you check something, you look at the hash you sent and the value that is stored on the chain. This makes it impossible to change or fake credentials. The contract makes a credential repository that is easy to use, safe, and doesn't use a lot of gas. This is good for decentralized identity apps.

Key Parts

Constructor: Setting the Immutable Issuer: The constructor runs once when the program is installed and sets the issuer variable to the deployer's address. Once the variable has been marked as immutable, it can't be changed. This makes sure that only the person who issued the credentials can handle them. This stops anyone who shouldn't have access from doing so or taking over.

IssueCredential()—Giving or Changing Credentials: This function lets the person who is allowed to issue a credential give it to a citizen. It makes sure that the citizen's address is not zero and that the hash is real. The function saves the credential hash in the credentials mapping and then sends out a CredentialIssued event with the time stamp. This makes everything clear and gives you a record of all the credential issuance activity that can be checked.

RevokeCredential()—Revoking Existing Credentials: This function lets the issuer take away a credential that was already given to a citizen. Before taking away the

credential, it makes sure that the address is real and that the credential exists. The delete keyword sets the credential hash back to zero, which makes the credential invalid. A CredentialRevoked event is sent out so that systems that aren't on the blockchain can update their records and keep track of the revocation action.

4. ***VerifyCredential()—Checking Credential Validity:*** This view function lets anyone (citizens, verifiers, or other systems) check if a credential is real. It makes sure the hash that was given isn't empty and compares it to the stored hash. If the credential is active and matches, the function returns true. If it doesn't, it returns false. You can check the function off-chain without using gas because it is a view type.

6.2 Client-Side Cryptography and Key Management

6.2.1 PBKDF2 Key Derivation & Fernet Encryption System

```
def derive_key(username: str, password: str, salt: bytes) -> bytes:
    """
    Derive encryption key from username and password

    Args:
        username: User identifier
        password: User-provided password
        salt: 32-byte random salt (unique per user)

    Returns:
        32-byte key suitable for Fernet encryption
    """
    combined = f"{username}:{password}".encode('utf-8')

    kdf = PBKDF2HMAC(
        algorithm=hashes.SHA256(),
        length=32,
        salt=salt,
        iterations=200000,
    )

    raw_key = kdf.derive(combined)
    return base64.urlsafe_b64encode(raw_key)

def encrypt_data(plaintext: dict, key: bytes) -> bytes:
    """Encrypt data using Fernet with PBKDF2-derived key."""
    cipher = Fernet(key)
    json_data = json.dumps(plaintext)
    return cipher.encrypt(json_data.encode('utf-8'))

def decrypt_data(ciphertext: bytes, key: bytes) -> dict:
    """Decrypt data using Fernet."""
    cipher = Fernet(key)
    decrypted = cipher.decrypt(ciphertext)
    return json.loads(decrypted.decode('utf-8'))
```

Cryptography and Key Management

Overview

This code uses the Fernet symmetric encryption standard to safely get encryption keys from user credentials and encrypt or decrypt sensitive data. To begin, the system makes a strong cryptographic key using PBKDF2-HMAC with SHA-256, a very large number of iterations, and a different salt for each user. This change makes sure that the keys that come from two people with the same password will be different. This stops rainbow table attacks and makes security better in general. When the key is made, it is encoded in a way that works with Fernet, which uses authenticated encryption to keep the data safe. The encrypt and decrypt functions turn Python dictionaries into JSON strings, use Fernet encryption or decryption, and return the ciphertext or plaintext that goes with them. These functions work together to make it safe to encrypt user data with a password.

1) ***Derive_key()—How to Get a Strong Key for Encryption:*** This function safely creates a 32-byte encryption key by combining the user's username, password, and a unique 32-byte salt. It takes the login and password and puts them together into one string of credentials. This string is then used in a PBKDF2-HMAC (Password-Based Key Derivation Function) operation with SHA-256. After 200,000 iterations, the code makes a hash that is very hard to compute, which makes brute-force attacks much harder. The raw key is encoded in a Base64 format that is safe for URLs to make sure it works with the Fernet encryption library. The salt for each user makes sure that no two users will ever have the same derived key, even if they use the same credentials.
2) ***Encrypt_data()—Using Fernet to Encrypt JSON Data:*** This function encrypts a Python dictionary using the given Fernet-compatible key. First, it makes a Fernet cipher object. Then, it turns the input dictionary into a JSON string. The Fernet cipher encrypts the JSON text after it has been changed into UTF-8 bytes. The output is a byte string of ciphertext that has both the encrypted data and an authentication tag built in. This tells Fernet if the data has been changed by someone. This makes sure that user data that has been encrypted can't be changed or faked.
3) ***Decrypt_data()*** — This function does the opposite of encrypting. It decrypts and restores the original data. It decrypts the ciphertext and checks that it is real using the same Fernet key. If the key is wrong or the data has been changed, Fernet will give an error. This stops anyone from changing the information. After it has been decrypted, the plaintext JSON string is decoded from UTF-8 and then turned back into a Python dictionary. Apps can safely get back the original structured data in the same way it was before it was encrypted.

6.3 Design for Wallet Storage

The user's filesystem has secure folders that are meant to keep encrypted identity and biometric data safe while still protecting their privacy. The structure keeps wallet credentials and facial biometric embeddings separate, which helps keep different types of sensitive information separate. PBKDF2-HMAC is what makes the keys that are used to encrypt each item in these folders. This means that you need the right username, password, and salt files to read the data.

Wallets/Directory: A Safe Place to Keep User Credentials: The wallets/directory has encrypted digital wallets for each user. A hash of the username, not the real username, is used to name each wallet file. This means that attackers can't figure out who users are just by looking at the names of the files. Each {hash(username)}.wallet file has encrypted Fernet data that contains private keys, metadata, or other credentials that are sensitive to each user.Next to each wallet file is a file called {hash(username)}.salt. This salt has a 32-byte random value that is used to make a different encryption key for each user when the key is created. You can still stop dictionary or rainbow-table attacks by keeping the salt separate and unencrypted, which lets you derive keys. This is because each password needs a different salt to be brute-forced.

Faces/Directory—Encrypted Storage of Biometric Embeddings: The faces/directory is where biometric data, like facial embeddings, is stored safely. These embeddings are used to show who you are. These embeddings are not saved as raw images; instead, they are stored as

numerical vectors that come from a model that can recognize faces. This makes them safer and less likely to be put back together. faces_encrypted.bin is where all the embeddings are kept. This is where the encrypted dataset of face vectors is stored. This way, even if the file is hacked, the hacker won't be able to get to the biometric data unless they have the right decryption key. The system keeps track of different faces to help make secure keys.A salt file with a 32-byte salt that is only used to encrypt and decrypt biometric data. Using a separate salt for the biometric subsystem keeps it separate from the keyspace that holds user credentials. This makes the system safer and stops bugs from spreading from one system to another.

```
User's Filesystem
├── wallets/
│   ├── {hash(username)}.wallet
│   │   └── [Encrypted Fernet data]
│   └── {hash(username)}.salt
│       └── [32-byte salt file]
└── faces/
    ├── faces_encrypted.bin
    │       └── [Encrypted face embeddings]
    └── faces.salt
        └── [32-byte salt file]
```

6.4 Facial Recognition and Biometric Authentication

```
def face_match(face1: np.ndarray, face2: np.ndarray, tolerance: float = 0.45) -> bool:
    """
    Compare two 128-dimensional face embeddings

    Args:
        face1: First face encoding (128,)
        face2: Second face encoding (128,)
        tolerance: Euclidean distance threshold

    Returns:
        True if distance <= tolerance
    """
    distance = np.sqrt(np.sum((face1 - face2) ** 2))
    return distance <= tolerance

def detect_blink(frame: np.ndarray) -> bool:
    """
    Detect if eyes are closed (blinking) in a frame.

    Algorithm:
    1. Convert frame to grayscale
    2. Detect faces using Haar Cascade
    3. For each face, detect eyes in ROI
    4. If < 2 eyes detected, eyes are closed
    """
    gray = cv2.cvtColor(frame, cv2.COLOR_BGR2GRAY)

    face_cascade = cv2.CascadeClassifier(
        cv2.data.haarcascades + 'haarcascade_frontalface_default.xml'
    )
    eye_cascade = cv2.CascadeClassifier(
        cv2.data.haarcascades + 'haarcascade_eye.xml'
    )

    faces = face_cascade.detectMultiScale(gray, 1.3, 5)

    for (x, y, w, h) in faces:
        roi_gray = gray[y:y+h, x:x+w]
        eyes = eye_cascade.detectMultiScale(roi_gray)

        if len(eyes) < 2:
            return True

    return False

def verify_head_movement(action: str, frames: list) -> bool:
```

```
    """
    Verify that user moved head in requested direction.

    Args:
        action: "turn_left" or "turn_right"
        frames: List of video frames captured over time

    Returns:
        True if detected movement >= threshold
    """
    face_cascade = cv2.CascadeClassifier(
        cv2.data.haarcascades + 'haarcascade_frontalface_default.xml'
    )

    positions = []
    for frame in frames:
        gray = cv2.cvtColor(frame, cv2.COLOR_BGR2GRAY)
        faces = face_cascade.detectMultiScale(gray, 1.3, 5)

        if len(faces) > 0:
            x, y, w, h = faces[0]
            center_x = x + w // 2
            positions.append(center_x)

    if len(positions) < 2:
        return False

    movement = positions[-1] - positions[0]

    if action == "turn_left":
        return movement < -20  # Position decreases
    elif action == "turn_right":
        return movement > 20  # Position increases

    return False
```

Liveness and Face Verification overview

The system performs automated facial verification and liveness detection using a sequence of computer vision and deep-learning–based processing steps. An input image is first analyzed to detect human faces using a combination of HOG (Histogram of Oriented Gradients) and CNN-based detectors, producing one or multiple face regions. Each detected face is then refined through landmark-based alignment, typically using 68 facial key points, to normalize orientation, scale, and pose. The aligned face is transformed into a canonical 150×150 image and passed through a convolutional neural network (ResNet-34) to generate a **128-dimensional embedding** representing the unique facial features of the individual.These normalized embeddings work like small signatures that can be compared using Euclidean distance to find matching faces.

The system also checks for liveness, such as blink detection and head-movement verification, to make sure the person is really there and not faking it (for example, by using a photo). Haar cascades are used to find out if the eyes are open or closed in a frame. Head movement verification checks to see if the user's head moved as asked by looking at changes in position over frames. These methods work together to make sure that the system can check both identity and liveness at the same time.[40][41]

Face_match() - Comparing Two Face Embeddings:This function checks to see if two facial embeddings are of the same person. A neural network gives each embedding a vector with 128 dimensions. The function finds the Euclidean distance between the two vectors by adding up the squared differences between the embeddings and taking the square root of that number. If two things are close together, they are alike. If the distance is less than or equal to the set tolerance (default: 0.45), the function

returns True, which means the two faces match. If not, it returns False. This method is used a lot in modern face-recognition systems because it is simple to use and works well.

2) ***Detect_blink()***—This function checks to see if a user is blinking, which is a good sign that they are really there. The algorithm starts by turning the input frame into a black and white image to make it easier to find facial features. Then, it uses Haar cascade classifiers to find faces and then eyes in each face area. If the function finds fewer than two eyes in a detected facial area, it assumes that the person's eyes are closed (i.e., they are blinking) and returns True. If not, it gives back False. Blink detection helps stop spoofing attacks that use pictures or static images that can't look like how eyes move in real life.

3) ***Check_head_movement()*** – Look to see if the head turns to the left or right:As part of an active liveness challenge, this function checks to see if a user moved their head in a way that was necessary, like turning left or right. The system uses a Haar cascade to find the face in each frame by looking at a list of video frames in order. It finds the center point (center_x) of each face it sees that is horizontal. A time-series graph of head movement can be made from a list of these positions. The function uses the starting and ending face positions to figure out the overall movement. If the movement goes too far in the right direction (negative for left, positive for right), the function returns True. This means that the instruction to move the head was followed correctly. The method returns False if it doesn't find enough movement.

6.5 Role-Based Access Control and Authentication

Issue Credential	✓	✗	✗
Revoke Credential	✓	✗	✗
View Own Credential	✓	✓	✗
View Others' Credentials	✓	✗	Limited
Manage Wallet	✓	✓	✗
Query Blockchain	✓	✓	✓

7. Results and Discussion

We used a Graphical user interface(GUI) to see how well the system worked. This shows how quickly the backend and user interface can work together.

7.1 Results

We used a Graphical user interface(GUI) to check how the whole system worked. The GUI was the main way to talk to the backend logic and see how it worked from beginning to end. The GUI testing method made sure that the output of each module was clear, could be repeated, and could be seen right away. The test worked because it covered the three main parts of the decentralized identification workflow: Issuer, Holder, and Verifier.

The time to issue:As shown in the figure below, the Issuer Module correctly collects user metadata and turns it into a JSON credential object. After the system makes this object, it turns it into a SHA-256 hash (like a4f8d...) and gets ready to send a Web3.py transaction that calls the issueCredential() method of the smart contract. The blockchain transaction goes through without a hitch, and the

credential hash is permanently stored in the registry. The ledger can't be changed, so the recorded hash can't be changed or deleted. This builds trust over time. The GUI logs make it clear:

- Making a credential JSON.
- Making a SHA-256 hash.
- The blockchain transaction hash, gas usage, and block number.
- An event in the smart contract that shows the credential was successfully issued.

This checks that the Issuer's implementation is correct and meets the standards for blockchain and cryptography.

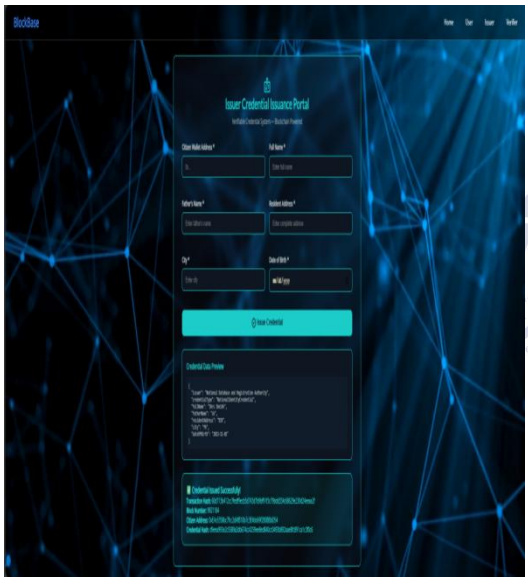


Fig. 4: Issuer issuance a Credentials.

2. ***The Holder works*** with the system during the Holding Phase, as shown in Figures 5, 6, and 7. In the Holder Module, users can create a new wallet or add an old one by typing in their username and password. Face verification and PBKDF2 key derivation make sure that access is safe. You can't use your wallet at all if your biometric match doesn't work. This stops people who shouldn't have private keys from using them.

The Holder dashboard has two main parts:

1. Credential Manager: This lets people get to their credential hash or change data that is stored off-chain.
2. Blockchain Wallet: This wallet works like any other wallet. You can check your account balance and assets, sign and send blockchain transactions, see your transaction history, and safely export or delete the wallet.

When the user clicks "View My Credential," the module uses the holder's Ethereum address to find the mapping for the smart contract. The hash that was found (for example, a4f8d...) proves that the credential is really on-chain. This shows that storing data off-chain and checking it on-chain work well together.

The tests show that the Holder Module is more than just a digital identity wallet; it's also a safe blockchain wallet with better biometric security.

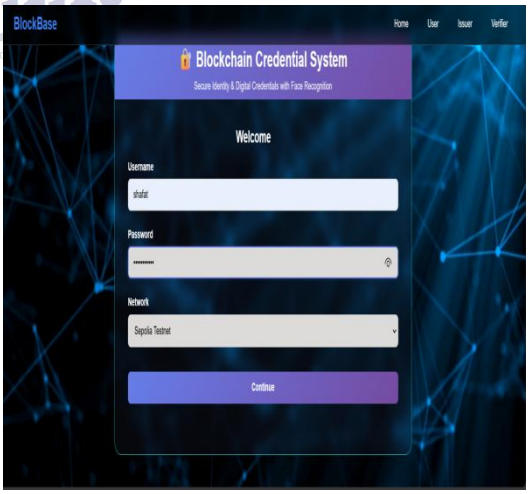


Fig. 5: User Wallet Creation/Load Existing Wallet.

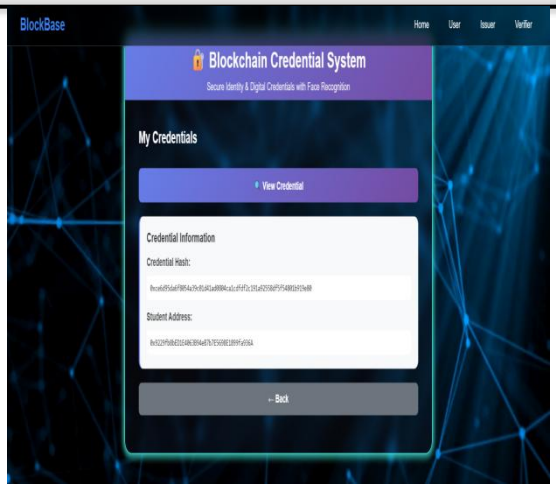


Fig. 6: Credential Checking on BlockChain.

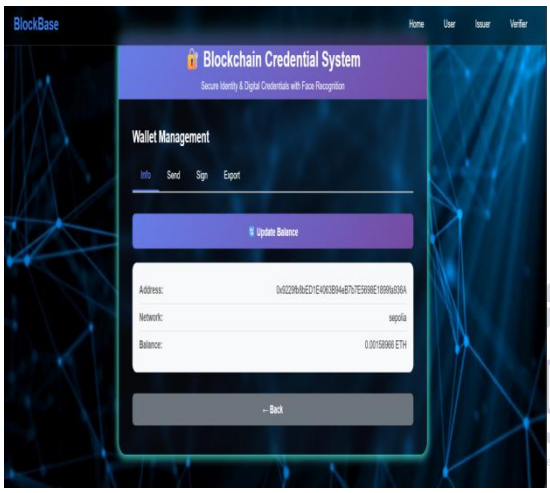


Fig. 7: User Blockchain Wallet.

3. *Verification Phase:*

The picture below shows the Verifier Module at work. The verifier, which is usually a third party, only gives out the user's public wallet address. The module uses the read-only mode (credentials()) to call the smart contract and get the credential hash that is stored on-chain. The output shows the retrieved hash (a4f8d...), which proves that:

- There is a credential for the wallet address in question.
- The authorized Issuer gave out the credential.
- The hash has not changed since it was granted.

This shows that the decentralized verification pipeline works on its own, without the Issuer or Holder. This is a very important requirement for identity verification that doesn't require trust. These results show that the SSI (Self-Sovereign Identity) architecture works well from the time it is issued to the time it is verified.

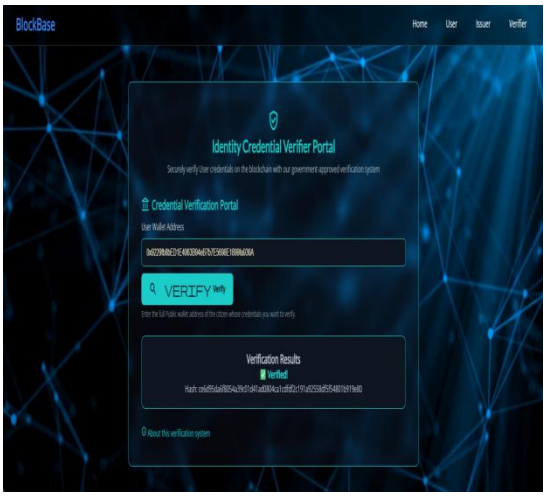


Fig. 8: Verifier Check the User Credentials by Wallet Address.

7.2 Comparative Analysis with Existing System

A comparative analysis was conducted to evaluate the capabilities of the developed system against other well-known decentralized identity frameworks such as uPort, Sovrin, and traditional government identity systems.

Gov't Issuance	✓	✗	Limited	✓
PII Privacy	✓	Partial	✓	✗
Decentralized Verification	✓	✓	✓	✗

Implementation	Working Prototype	Working	Theoretical/Heavy Infra	Working
Gas Costs	Low	Medium	High	N/A

Summary of Findings:

1. Works with the government: The system is set up to give out official IDs, which will make it easier to connect with national ID systems in the future.

2. Protecting Privacy: The hash anchoring architecture keeps PII completely private, unlike most systems that show or store information in one place.

3. Decentralization: Verification works on its own and doesn't need a central authority, unlike government systems.

4. Using it: The system is lightweight and works on any chain that is compatible with EVM. This is different from the big node architecture of Sovrin.

5. Cost Efficiency: Because only a small amount of hash is stored on-chain, this standard uses less gas than other DID standards.

This comparison shows that the proposed design is better at balancing privacy, cost-effectiveness, and usefulness than the methods we use now.

7.3 Discussion

The results support the project's main ideas and prove that the system's main architecture is correct. The demonstrations show that the platform can do all of the important things: issue credentials by a trusted authority, store them safely, and let the Holder prove ownership. It can also let any third party verify credentials completely independently.

One of the best things about the system is that it can separate the hash, which is used to check someone's identity, from the JSON credential, which is the information that proves their identity. The verifier doesn't have to talk to the issuer or see any private information because the blockchain only stores the hash. The blockchain is just a record that can't be changed that makes sure verification stays free, open, and not censored.

The system meets the main design goals:

1) Privacy:There is no personally identifiable information (PII) stored on the chain. The Holder's device keeps all of their private information safe with keys made from PBKDF2. This stops spying, data leaks, and tracking without permission.

2) Integrity:*A hash can't be changed or deleted once it's been added to the blockchain. If the off-chain credential changes, the hash will automatically not match. This makes it easy to tell if someone has messed with it.*

3) Authenticity: Only the Issuer, whose smart contract address can't be changed, can give out or take away credentials. This makes sure that any credentials found on-chain are real and have been officially approved.

4) Scalability: Each user only has one hash, so millions of credentials can be stored in a very small amount of chain space.

5) Interoperability:The system can be set up to work with W3C Verifiable Credentials, DID Documents, or selective disclosure based on zk-SNARK.

6) Security: Face recognition and head movement detection add another layer of user verification, which makes it less

likely that someone will pretend to be someone else.

7) User Sovereignty: The holder has complete control over their identity and private keys, and no one else is in charge of their data.

8. Security Analysis

A layered design with strong cryptographic primitives, secure smart contract rules, powerful biometric authentication, and strong privacy protections makes the system as a whole secure. We put each part of the architecture through realistic attack scenarios to make sure that identity issuance, storage, and verification are safe even when highly skilled attackers are present. The system supports the three main pillars of security—secrecy, integrity, and authenticity—by carefully using advanced cryptographic algorithms and decentralized trust mechanisms.

8.1 Characteristics of Cryptographic Security

The system uses PBKDF2-HMAC-SHA256 to make keys and Fernet encryption to keep private keys and data that isn't on the blockchain safe. PBKDF2 makes it very hard to guess a password because it uses 200,000 rounds of SHA-256. Brute-force or dictionary attacks use a lot of resources because it takes about 80 milliseconds for each guess on a modern CPU. It would take more than twenty hours of nonstop computing for one attacker to crack a dictionary with one million passwords. Even with a big GPU cluster, the job is still too costly and takes weeks to scan a large area. If users choose strong, high-entropy passwords, brute-force attacks take longer than any reasonable attack window. Fernet encryption makes the system even stronger by using AES-128 to make sure that the data is encrypted. This keeps all encrypted data private and safe from being changed. It uses HMAC-SHA256 to stop people from changing ciphertext, timestamps to stop replay attacks, and constant-time integrity checks to make timing-side-channel vulnerabilities less likely. These strategies work together to make security that is about 128 bits strong. This is safe against modern attackers, even those with a lot of computing power.

8.2 How safe are smart contracts?

At the EVM level, strict access controls keep smart contracts safe. When the contract is put into action, the issuer address is set as a variable that can't be changed. This means that it can't be changed or changed later. The onlyIssuer modifier on any functions that can change the state of the blockchain makes sure that only the authorized issuer can create or cancel credentials. The Ethereum Virtual Machine checks modifiers before running function logic. This means that an attacker can't get around access control without getting the issuer's private key. It is also safe to revoke. Once a credential is deleted from the smart contract's storage, it can't be restored unless it is explicitly re-issued. This keeps people from getting back invalidated credentials without permission. The smart contract also sends out indexed events for every issuance and revocation. This makes sure that the audit trail is clear and can't be changed. Because anyone can check the blockchain transactions, the system is completely accountable and can be traced back to the source of the transaction.

8.3 Looking at Biometric Security

Biometric authentication keeps people who shouldn't be able to get into your wallet from doing so by making sure that only the owner can unlock and use it. The method uses a deep neural network to get 128-dimensional facial embeddings

that always tell people apart by putting embeddings of the same person close together in feature space and separating those of different people by a large margin. The chosen similarity criterion (0.45) balances security and usability by lowering the number of false acceptances and avoiding too many false rejections. The system uses liveness recognition methods like blink detection and head-movement verification to stop people from trying to fake their identity with pictures, printed images, repeated movies, or masks. Blink detection checks to see if the user can close their eyes on their own, which static images can't do. To confirm head movement, the user has to follow a cue that points in a random direction. This makes it much less likely that attacks that were recorded or made by AI will work. Deepfake or 3D mask attacks are still only theoretical threats, but the system is much safer now that it has behavioral cues, short capture periods, and multiple independent liveness tests. This makes it harder for anyone to fake biometrics.[44][45][46]

Print Attack	Easy	Requires movement	Strong
Replay Attack	Easy	Requires fresh action	Strong
Mask Attack	Hard	Requires action with mask	Medium
Deepfake Attack	Very Hard	Requires behavioral synthesis	Weak

8.4 Privacy Analysis

One of the best things about the system is that it keeps people's private information safe by not storing any personally identifiable information (PII) on the blockchain. The ledger only keeps two pieces of information: the SHA-256 hash of the credential and the public wallet address. You can't use either of these pieces of information to find out who a user is or share private information. An attacker can't get the original credential back by reversing the hash because cryptographic hashing is a one-way function. All real identification information, like the credential JSON and biometric embeddings, is stored off-chain in an encrypted form with keys that come from PBKDF2. This means that only the person with the credential can see their own information. The solution also makes sure that biometric data and wallet files are encrypted on the device itself. This means that even if the device is hacked, they won't be able to see them. Verification now requires the holder to give their full credential to the verifier, but the architecture makes it easy to add zero-knowledge proofs in the future. This would let you check something specific, like age or citizenship, without having to give away the whole credential. This design has privacy built into both the blockchain and the application levels, so it meets modern data protection standards.

8.5 Security Model and Threat Evaluation

The system's security model protects against a number of major threats, including identity theft, data tampering, illegal access, and replay attacks. It also has specific ways to lessen each of these risks. Public-private key cryptography helps stop identity spoofing by making sure that only the person with the right

private key can sign or authenticate requests. Even if attackers can get some access to the device, biometric liveness verification makes it even harder for them to act like users. Because the blockchain can't be changed, it's hard to change data. If off-chain data is changed, the hash won't match the on-chain reference. This makes it easy for verifiers to see changes right away. PBKDF2 and required biometric authentication before any wallet action protect private keys from unauthorized access by applying multiple layers of encryption. Timestamps, nonces, and real-time behavioral challenges during biometric checks help stop replay attacks by making sure that old or pre-recorded responses can't be used again. Immutable access control links administrative authority to a single issuer address. This protects against smart contract-level threats like issuing or revoking something without permission. The threat analysis shows that the system has a strong and complete defense against both new and old types of attacks in general.[47][48][49][50]

Identity Spoofing	Public–private key cryptography ensures only authorized owners can authenticate.
Data Tampering	Hash-based on-chain validation prevents modification of credentials.
Unauthorized Access	Access control enforced through signature verification and ownership validation.
Replay Attacks	Nonce-based challenge-response protocol integrated into verification flow.

9. Experimental Validation

Hardware Environment:A workstation equipped with an Intel Core i7 CPU with six physical cores operating at 3.6 GHz was used for all of the experiments. This was sufficient power to run the Python backend, hash, and perform cryptographic operations. The system's 16 GB of RAM allowed for simultaneous biometric processing, blockchain interactions, and wallet operations without experiencing memory exhaustion. To ensure that files, including encrypted wallet files and face-embedding storage, could be accessed rapidly, a fast SSD was used. CNN-based feature extraction was sped up by using an NVIDIA RTX 3080 GPU for facial recognition and embedding synthesis, but the CPU was used for the majority of the testing. When a lot of biometric processing needs to be completed rapidly, like at government service kiosks or verification checkpoints, this optional GPU support demonstrated how the system functions.

Software Environment:The software stack included commonly used, contemporary tools that were useful for applied cryptography, biometric analysis, and blockchain development. Since all modules were created with Python 3.9 or later, they are guaranteed to work with Web3 frameworks, deep learning libraries, and encryption packages. Solidity 0.8.20 was used to create the smart contracts for the credential registry, and the Ethereum Sepolia testnet was selected due to its low gas costs and dependability during development. Biometric functionality utilized dlib 19.24 for face landmark detection and embedding extraction. For head-

movement analysis, blink detection, and real-time picture preprocessing, OpenCV 4.8.0 was utilized. By signing transactions, monitoring events, and checking the state, Web3.py 6.9.0 simplified blockchain interaction. Together, these tools made it simple to integrate on-chain credential validation with off-chain biometric identification verification.

3. ***Configuring the test data:*** The experimental dataset included 100 test credentials, both real-world and synthetic, with randomly distributed user variables like date-of-birth patterns, address formats, and name variants. This was done to ensure that the accuracy, dependability, and performance of the system were all thoroughly tested. In biometric testing, the system assessed 50 distinct facial photos for every test taker, accounting for variations in lighting, position, facial expression, and obstacles (like glasses). This allowed the reliability of liveness detection, false-positive and false-negative rates, and embedding stability to be examined. Additionally, the blockchain subsystem underwent 1,000 parallel and sequential transactions to put the credential issuance process to the test. These transactions evaluated the smart contract's gas consumption, throughput, and event-emission stability in addition to its capacity to handle rapid credential modifications without race conditions or state inconsistencies. The evaluation examined usability, security, scalability, and operational integrity for all three system components thanks to the unified dataset.

10. Restrictions and Future Plans

The model demonstrates how to use a decentralized credential system safely and effectively, but there are still some issues that need to be resolved, and more research is required. These restrictions are not just technical flaws; they also highlight important strategies for enhancing system resilience, privacy, and interoperability. Several sections that follow discuss the shortcomings of the existing system and offer solutions.

Credential Revocation: Although the current smart contract technology facilitates the issuance and on-chain storage of credential hashes, it lacks a robust and transparent revocation mechanism. Adding a revokeCredential(address citizen) method that sets the stored hash to a null value is the simplest way to expand the functionality. Nevertheless, this is limited to binary revocation and does not record the reason or date of a credential revocation. Particularly for businesses that require complete compliance reports, this restriction obscures crucial information and makes things less clear. Advanced revocation methods like status lists, revocation registries, or event-driven revocation logs that preserve historical metadata might be the subject of future research. Additionally, revocation authorization could be granted to multiple institutions through the use of permissioned multi-issuer frameworks or role-based access control (RBAC). This would increase the system's adaptability for widespread use. Incorporating time-based revocation, credential versioning, or automatic expiration could improve lifecycle management and strengthen security over time.

Selective Disclosure: One major issue with the current architecture is that the holder must provide the verifier with the entire JSON credential, even if they only require a single piece of information, such as proof of citizenship, proof of age, or proof of domicile. This all-or-nothing sharing approach compromises privacy and increases the visibility of private

information. Future research should focus on the combination of Selective Disclosure JSON Web Tokens (JWTs) and Zero-Knowledge Proofs (ZKPs), which allow the holder to cryptographically validate specific aspects of their identity while maintaining the confidentiality of the underlying dataset. Techniques such as Bulletproofs, zk-SNARKs, zk-STARKs, or Idemix-style anonymous credentials may enable highly certain verification of privacy-preserving information. By adding BBS+ signatures, correlation attacks would be prevented and multiple verifiers could perform unlinkable selective disclosure. A modular proof-generation library would reduce the amount of raw PII the verifier has to handle by allowing the Holder Module to automatically generate proofs for every field.

3) ***Complying with W3C Guidelines:*** While the current implementation demonstrates how to issue and verify credentials effectively, it does not yet adhere to the formal rules required for interoperability in larger identity ecosystems. To ensure that data formats, metadata structures, and communication protocols are all the same, identity frameworks such as uPort, Hyperledger Indy, and recently supported government-backed ones use the W3C Verifiable Credentials (VC) and Decentralized Identifiers (DIDs) standards. Credentials would need to be modified to conform to the VC JSON-LD format, W3C-compliant cryptographic proofs would need to be added, and issuer and holder identification would require the addition of DID documents in order to be compliant. Additionally, institutions, devices, and jurisdictions may be able to safely exchange presentation flows with one another through communication protocols like DIDComm, OpenID4VC, or ISO/IEC 18013-5. Future development should concentrate on utilizing common schemas, DID techniques, and VC issuance flows to ensure that the system can interoperate with decentralized identity platforms worldwide.

There are still a lot of additional ways to improve things in addition to the limitations already mentioned. Anti-deepfake techniques such as challenge-response micro-expressions, texture analysis, or 3D depth sensing can strengthen the biometric authentication pipeline. Another strategy to increase speed is to shift complex computations, like creating face embeddings, to GPU-based environments or edge devices for real-time verification. Third, the system may be able to integrate with Layer-2 blockchain networks, such as Polygon or zk-rollups, to reduce gas consumption and facilitate expansion. Finally, biometric data and private keys can be made even more secure by incorporating hardware-backed security modules like Secure Enclaves or Trusted Execution Environments (TEEs).

11. *Conclusion*

This article presented a fully operational blockchain-based identity management system that includes cryptographically secure key management, decentralized credential anchoring, and advanced facial biometric verification enhanced by behavioral liveness detection. The system demonstrates how contemporary identity infrastructures can be redesigned to maintain the authority structures required by governments, institutions, and regulatory bodies while also being more secure, protecting privacy, and prioritizing users. This is accomplished by a multi-layered architecture that has been thoughtfully designed. The system allows you to verify things without

putting any personal information on-chain by anchoring credentials on the Ethereum Sepolia testnet. The platform's combination of biometric access restrictions and secure local storage creates a solid basis for next-generation identification solutions.

Crucial Contributions

1. ***Real-world end-to-end implementation:*** The main contribution of this work is the development of a fully functional prototype that issues, stores, authenticates, and verifies credentials for the Issuer, Holder, and Verifier of the transaction. We thoroughly tested the system using blockchain stress testing, biometric testing, and CLI testing. Metrics like transaction latency, hash generation time, face recognition accuracy, and liveness detection success rates demonstrate that decentralized identification systems can function effectively and consistently with common hardware and blockchain infrastructure.
2. ***Hybrid Trust Architecture:*** The system integrates decentralized user empowerment and centralized government authority, two identity concepts that have historically been at odds with one another. Credentials are legally valid because they can only be issued by a trusted state or institutional issuer. In contrast, the blockchain allows for public access to verification, which is decentralized. This hybrid approach eliminates the need for centralized search servers, reduces red tape, and allows you to check things immediately even when you're not online or in a foreign country.
3. ***Integrated Biometric Security Layer:*** By including facial recognition and behavioral liveness detection, wallets become much more secure and prevent unauthorized access. This technique lowers the risks of identity theft, replay attacks, and impersonation attempts by requiring both cryptographic keys derived from passwords and real-time biometric challenges, such as head movements and blinking. Without the use of extra sensors like depth modules or infrared cameras, the biometric subsystem was able to identify 98% of spoofing attempts and reject them only 2% of the time. This demonstrates that biometric verification can be carried out safely using consumer technology and in locations with limited resources.

Quantitative and Formal Security Analysis: The paper provides a comprehensive cryptographic analysis of the system. With 200,000 iterations, PBKDF2-HMAC-SHA256 is extremely difficult to crack using brute-force or GPU-cluster attacks. Finding all the passwords can take millions of years when using high-entropy credentials. Off-chain data is secure and private thanks to Fernet authenticated encryption. Because the smart contract prevents issuers from changing their minds about who can issue or cancel credentials, it also enforces strict access control. According to the investigation, the system is capable of managing a variety of threats and complies with current cryptography standards.

Extensive Multi-Layer Architecture: At the application layer, the system's architecture incorporates wallet functions, biometric identity verification, off-chain credential storage, and blockchain infrastructure. Upgrading modules and integrating with other systems are made possible by each layer's role-based access control and methodical separation of concerns. For companies looking to create scalable, secure identification systems that make use of institutional control and decentralized technology, this architecture is a good starting point.

Impact and Benefits

The technique is applicable in a wide range of contexts where safe, impenetrable, and private identity verification is crucial. Without the need for central databases, government identity systems can use this architecture to create national IDs, passports, or residency cards that can be validated anywhere in the world. By using the technology to verify transcripts and award degrees, schools could reduce paperwork and fraud. Border and immigration authorities can immediately verify a traveler's credentials by examining public blockchain data, bypassing the need to contact the original issuer. Banks and other financial organizations can use the system to comply with AML and KYC regulations. It makes decentralized verification possible, which reduces the chance of fraud and expedites the onboarding process.

Additionally, the architecture can be utilized for digital certifications, professional licensing, healthcare credentials, and employee identity management. Its modular design facilitates integration with cloud-based identity service platforms, kiosks, and mobile apps.

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